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ВЫБОР ПЛОЩАДКИ ДЛЯ УСТАНОВКИ СОЛНЕЧНОЙ ФОТОЭЛЕКТРИЧЕСКОЙ СИСТЕМЫ С ПОМОЩЬЮ МОДЕЛИ АНАЛИТИЧЕСКОГО ИЕРАРХИЧЕСКОГО ПРОЦЕССА В АЗЕРБАЙДЖАНЕ

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Наиболее подходящие места для установки солнечных фотоэлектрических установок определяются путем всестороннего анализа метеорологических, экономических и экологических критериев областей энергетического потенциала. Основные критерии выбора местоположения оцениваются с использованием модели аналитического иерархического процесса, основанной на методах многокритериального принятия решений для крупномасштабных солнечных фотоэлектрических проектов. Этот метод учитывает различные факторы, в том числе производственные и технологические, направленные на получение максимальной прибыли в краткосрочном периоде от проекта и производительность выработки электроэнергии. Модель аналитического иерархического процесса также применяется для оценки областей с высоким солнечным потенциалом и факторов, которые являются основными критериями для расчета индекса пригодности площадки. В исследовании определен коэффициент соответствия подходящих мест и оценены альтернативы для строительства фотоэлектрических установок. Помимо сопоставления метеорологических данных и спутниковых измерений (MERRA-2, GEOS-5.12.4), значения радиации были получены расчетным путем с помощью инструмента «область солнечного излучения» в ГИС на основе цифровой модели рельефа. Применив инструмент «взвешенное наложение» на основе ArcGIS, был сделан вывод, что 1,17 % (1016,8 км^2) территории страны являются наиболее подходящими участками для установки солнечных фотоэлектрических систем. К этим районам в основном относятся зоны Хызы, Гобустана, Гаджигабула, Бейлагана, Шарура, Бабека и Джейранчёля. Всего в стране выявлено 40 участков с разным уровнем пригодности. Восемь из этих участков, расположенных в Нахичеванской Автономной Республике, имеют высокий уровень пригодности и занимают 11 % (109,2 км^2) от всей определенной территории. Площадь остальных участков со средним и низким энергетическим потенциалом составляет 28 % (284,6 км^2) и 61 % (623 км^2) соответственно. Установка фотоэлектрических панелей на всех выявленных участках даст возможность полностью удовлетворить потребности страны в энергии.

Ключевые слова: возобновляемые источники энергии; солнечная энергия; солнечная фотоэлектрическая система; многокритериальное принятие решений; модель ГИС; модель АИП.

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SITE SELECTION FOR SOLAR PHOTOVOLTAIC SYSTEM INSTALLATION USING ANALYTICAL HIERARCHY PROCESS MODEL IN AZERBAIJAN

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The most suitable sites for solar photovoltaic power installations are determined through a comprehensive assessment of the meteorological, economic and environmental criteria of the energy potential areas. The basic criteria for location selection are evaluated using an analytical hierarchy process method based on multi-criteria decision-making technique for large-scale solar photovoltaic projects. The analytical hierarchy process model is also applied to evaluate areas of high solar potential and factors that are primary criteria for determinate the site suitability index modelling. This method considers various conditions, such as production and technological considerations, which aim to maximise the short-term profit from the project and the efficiency of power generation. In the study, a consistency ratio of suitable localities was determined and proper alternatives for the construction of photovoltaic installations were evaluated. In addition to local meteorology and related satellite measurement data, the country's radiation values also were compared by converting a digital elevation model data using the tool «Area solar radiation» in GIS. As a result of calculating the site suitability index with the ArcGIS weighted overlay tool, it was concluded that 1.17 % (1016.8 km^2) of the country are the most suitable sites for the installation of solar PV systems. These areas mainly include Khizi, Gobustan, Hajigabul, Beylagan, Sharur, Babek and Jeyranchol zones. The total number of locations identified accross the country, classified into 3 categories according to their level of suitability, includes 40 sites. Eight of these high suitability sites, all in Nakhchivan Autonomous Republic, contain 11 % (109.2 km^2) of the total potential area. The remaining 32 sites, corresponding to areas with medium and low energy potential, cover 28 % (284.6 km^2) and 61 % (623 km^2), respectively. When these areas are completely covered with PV panels, it will be possible to fully supply the energy demand of the country with solar energy.

Keywords: renewable energy resources; solar energy; solar photovoltaic system; multi-criteria decision-making; GIS model; AHP model.

Introduction

Many countries have created renewable energy systems (RES) portfolios to fully utilise alternative energy sources for a more sustainable, reliable and low carbon emission future. Solar photovoltaic (PV) technology has become one of the fastest-growing renewable energy sources worldwide, with 628 GW installation power in 2019. Therefore, PV module prices have decreased by 50 % in the last 10 years, and the energy production of solar power PV plants has increased 15 times more [1]. Given the prospect of ongoing technological development in PV panels, prices are expected to decline further, including the cost of production and the impact of photovoltaic systems on market expansion [2].

The major obstacle to the development of solar energy is the low intensity of solar radiation, the low capacity factor (CF) of the solar panels, and the high initial installation cost [3]. The primary factors in choosing the installation site of the solar power plant are to determine the most suitable location where the power output from the PV panels is highest and the total cost of the project can be minimised. It can facilitate the selection of suitable locations for grid-connected PV solar systems by examining key factors in the project design process by applying multi-criteria decision-making (MCDM) technique to analyse certain criteria that affect site selection. Utility-scale PV projects can be defined as large-scale plants capable of generating electricity with a minimum power capacity of 5 MW [4; 5].

As an example of optimal location selection with this method, Azizkhani et al. [6] have selected suitable locations according to four categories, including the value of solar radiation, economic characteristics, technical factors, and geographic considerations. These factors were analysed with the analytical hierarchy process (AHP) and a map of potential areas was created. This method is the relative measurement theory of abstract measures for large-scale, multi-functional and multi-dimensional decision analysis developed by T. L. Saaty in 1980 [7]. As a result, the provinces of Sistani and Baluchistan (Iran) were determined to have high install potential for photovoltaic power plants.

In the current times, the use of geographical information systems (GIS) for the development of renewable energy resources is increasingly widespread. Regarding these studies, Noorollahi et al. [8] have performed the research in two stages to determine suitable sites. In the first stage, buffer zones were created according to the restrictions determined for non-compliant areas. In the next step, has been determined the suitability of regions according to solar radiation, average annual temperature, altitude, slope, land use, average annual cloudy days, distance to power lines, main roads, and settlements. The comparative weights of the selected criteria and sub-criteria were calculated using the AHP model. By then applying weighted overlay modelling these criteria, the final priority map of different regions of Iran was prepared for the use of solar photovoltaic facilities and it was determined that 7 % of the area is suitable for PV stations.

Since a comprehensive assessment of areas with high-energy potential for solar PV plants is based on various research and relevant data, the most suitable location is determined in the following order:

- determining decision criteria and constraints for site selection research;
- designing the selection of optimum locations on a project basis;
- identifying of site suitability index values by weighting decision criteria;
- creating final maps by evaluating the basic criteria of suitable locations.

Regarding the above factors, a decision model was proposed with the AHP method by creating a database in GIS related to meteorology, relief, environment and land use of solar PV potential regions in Saudi Arabia, and it was tried to determine the areas at a large-scale [9]. Such a methodical approach will provide alternative selection combinations of different subjective and contradictory components that can benefit decision-makers (DMs) in determining the suitable location in the location selection process.

Based on the relevant studies and suggested techniques in the selection of the suitable site, the following factors were investigated:

- criterion grid layers of suitable areas are created with help of ArcGIS spatial analyst tools using local and related satellite meteorological data;
- with the GIS-based MCDM technique, industrial and infrastructure features of certain sized areas and environmental conditions that adversely affect solar panels are taken into consideration;
- in PV power installation projects, regions with high irradiation values are selected as the primary indicator in site selection;
- by applying weighted overlap of the relevant criteria, the compliance level of the suitable zones for the installation of power plants is determined and a result map is created.

Most of the studies for the installation of solar panels consider the solar energy potential as one of the most effective decision-making measures. The basic criterion for establishing large-scale photovoltaic power plants is the very high solar irradiation values. For example, in regions with high solar energy potential in Azerbaijan, annual global horizontal irradiation (GHI) values vary between 1400–1750 kW · h/m^2. PV technology can operate in the presence of both direct normal irradiation (DNI) and diffuse horizontal irradiation solar radiation, unlike concentrating solar thermal technology, which uses only direct normal irradiation [10; 11].

The most suitable locations for solar power plants are areas of high in solar energy with an annual solar radiation flux of at least 2000 kW · h/m^2 of a horizontal surface with a sunshine duration of 2400–3500 h per year [12]. By utilising these potential areas economically, it is imperative to minimise the distance from the station to energy transmission lines and energy loss during transportation due to the high cost of infrastructure installation for solar power plants. Because RES should support the economic development of the region, where it is installed and provide long-term benefits due to its environmental effects [13]. In addition, although PV plants established close to urban settlements contribute to the cleanliness of the city atmosphere, electricity supply also should be provided at a lower cost [14].

Researches based on MCDM methods on the selection of suitable location make it easy to choose the most suitable alternative among the options created by weighting many principles together. This technique is applied in particular in the selection of the optimum location by determining the environmental, technical and industrial aspects of the fields in the RES project design (table 1). Site selection for a station based on a single factor will create negative economic and environmental impacts on the region. As a solution to this problem, Colak et al. [15] specifically suggested the AHP model for choosing the appropriate location among MCDM methods in his research on electrical project installation complexity. For this purpose, the spatial data of the high-energy potential lands have been included and an important requirement has been achieved in determining the consistency rate for the deployment of large-scale solar power plants.

For the development of a solar power plant installation project, areas with a minimum annual DNI value of 1200 kW · h/m^2, 2500 h of sunlight per year and corresponding to a high atmospheric clarity index are selected. In addition to these, the following factors are also examined:

- projected energy potential zones, flat ground areas without natural shadow effect, and at an angle to the south direction should be preferred;
- sites selected for low investment should be areas close to transportation, electricity transmission lines, industrial units and settlements;
- protected zones and unsuitable terrain areas should be excluded from research areas and industrial activities that affect natural life should be avoided;
- electricity users should be provided with stimulating cost benefits to develop incentives for the positioning of solar power plants and to encourage environmentally friendly and clean-sourced energy use.

It is possible to reach a conclusion in determining the regions of high solar irradiation by applying the combination of GIS and AHP for optimum location selection in solar power plant installation studies. For example, approaches to this method have been applied in the National Renewable Energy Laboratory research on the utility estimation of solar concentrated thermal power in the southwestern USA [5]. In study, after the restrictions such as national parks, slope, transmission, and distance to agricultural areas were determined, suitability level maps for solar power plants were created and suitable areas for the project were determined. As an example of research techniques with MCDM, Sengupta et al. [16] analysed the role of GIS and AHP spatial systems in variation formulation and presented a formula for their assimilation. Randal et al. [17] proposed research pathways and developed the Site Suitability Model in combination with AHP's GIS program to facilitate the selection of suitable sites. Rumbayan et al. [18] identified optimal areas using GIS-based MCDM technique to install RES (solar, wind and geothermal) in 30 regions of Indonesia, taking into account energy service principles. Effat [14] conducted an AHP assessment to measure the impact on the appropriate field assessment and determine the level of field cohesion using GIS-based spatial analysis tools. Uyan [18] in Karaman (Turkey) the deployment of appropriate land use solar power plants, local weather conditions, proximity to electrical lines are defined according to agricultural facilities and environmental protection. In study, evaluation made using MCDM methods revealed that 6.23 % of the area is the most suitable.

Table 1

Site suitability criteria for solar PV installation

Basic criteria	Sub-criteria	Restrictive criteria	References
Environmental	Land use	Fertile soil	[20; 21]
	Agricultural suitability	Cultivated land	[18]
	Distance to protection areas	Natural, biological, historical and archaeological sites	[20]
	Population density	Residential areas	[14]
Infrastructure	Distance to settlement areas	>1 km	[21; 22]
	Distance to the transformer centre	Average >15 km	[13]
	Distance to main roads	>5 km	[14; 20]
	Distance to transmission lines	>10 km	[19; 22]
Economic	Land suitability	Areas suitable for agriculture	[23]
	PV system construction cost	>1.850 $/kW	[23]
Climatic	Solar irradiation	Irradiation $\leq$1400 kW · h/m^2	[24]
	Average temperature	Daily >25 °C	[25]
Orography	Slope	>5°	[21; 26]
	Terrain relief	Plains Mountainous areas	[21]
	Orientation (aspect, tilt)	Spatial aspects	[14]

Colak et al. [15] researched suitable areas for the installation of solar photovoltaic power plants with GIS technology in Malatya province. For this purpose, many impact factors such as solar energy potential, roads, energy transmission lines, transformer centers, slope, facade, dams and river valleys, natural gas pipelines, land cover and residential areas have been analysed. Factor weights were calculated using the AHP method and a suitable map showing the most suitable locations was provided. Charabi et al. [21] prepared an assessment of sites suitability for the implementation of PV installations in Oman. In the study, indeterminate quantifiers were appropriate areas which were determined by combining a sequential weighted overlay tool. Aydin et al. [26] evaluated a decision-making method that uses the consecutive model builder algorithm to calculate optimal areas for solar PV and wind farms by combining various criteria. With this method, multi-criteria technique studies on GIS were applied to determine the areas where Colorado wind and solar potential areas were established [27]. In the research [20], a large area of southern England was evaluated power generation capacity in combination with suitable locations AHP and GIS for wind and solar stations. In another study, proposes the application of a MCDM model to select the best zone for the installation of river hydroelectric plants in Vietnam. The most widely used of these techniques are the fuzzy analytical network process and the technique for order of preference by similarity to ideal solution. As a result, Nghe An (LOC05) is found to be the optimal solution for selecting river portions where hydroelectric plants are viable in Vietnam [28].

Materials and methods

In the study, the solar irradiation and meteorological data for determining the optimal areas were taken from Global Solar Atlas (GSA) [10], SolarGIS [11], Azerbaijan Geographical Atlas [29], and MERRA-2, GEOS-5.12.4 based on NASA satellite [30]. By examining the solar irradiation data, maps by ArcGIS spatial analyst tools were created and the site suitability index for PV power plants was determined using MCDM technique for the first time in the country. The most suitable localities for the site of PV solar power installation in the following order was analysed in the applied of a four-stage flow chart in study:

- map-weighted overlay approach has been applied in the GIS environment based on the criteria established to determine the relevant areas;
- applying with the AHP model alternatives for each criterion, importance and priority weights in field selection were determined;
- in the third stage, energy potential areas were evaluated by the purpose by applying the model builder procedure in the ArcGIS application;
- the core concept of the MCDM technique includes superimposing various criteria data, considering the entry criteria formed, and comparable weights from AHP to realise an integrated analysis. The weighted sum grid layer takes the scaled data entries, weights the input layers, and combines them. As result, to generate the suitability index map, the result got with the reclassification tool were classified between 1 (least suitable) and 4 (most suitable) levels.

Restrictions on suitable site selection. The tilt angle of PV panels towards the sun, which significantly increases the CF in solar energy production, is the most important impression among the technical feasibility criteria and requires the selection of appropriate orientation areas. Based on this factor, other criteria to be considered in the selection of suitable areas are proximity to residential areas, proximity to highways, proximity to energy systems, terrain relief, land use, etc. (fig. 3).

Since the choice of location depends primarily on high DNI, medium-high energy potential zones were identified throughout the country. For this purpose, a solar irradiation map was created by transforming the Solargis, local meteorology observe measurement (1990–2015) and NASA based MERRA-2 satellite data with the solar analyst tool in ArcGIS [11; 30]. In addition, a comparative combination of GSA and meteorology measurement data was made to obtain a concrete value. To model the zones of potential solar radiation with the solar analysis tool, the site consistency values were defined between the layers created by considering local factors such as angle, slope, and meteorological conditions [31]. Physical terrain data layers of ASTER GDEM with 30-meter resolution was used and create an area elevation map (fig. 1) [32]. As seen from the map, based on GHI measurements, the annual total radiation values across the country vary between 705–1776 kW · h/m^2. Potential areas for solar panels installation sites with medium-high CFs include locations over 1400 kW · h/m^2. Since the air temperature for the most efficient energy generation of PV panels in all regions with high-energy potential is 25 °C, it is one of the primary factors to be considered in choosing suitable sites for plant installation in areas with an annual average temperature of 10–18 °C [29].

The slope and relief characteristics of the area are accepted as an important criteria to prevent high installation costs in high slope zones compared to flat or slightly steep slopes in a suitable site selection. Since PV power plants require wide usage areas (approximately, 1 MV – 21 000 m^2), it is more beneficial to deploy them in flat areas due to their low economic feasibility compared to sloping areas. Since the slope up to 5° and the south direction areas are more opportune in the site selection for solar power plants, the optimal location and directions of such regions are determined using DEM data [32]. DEM data of the ASTER GDEM satellite was used for this. This data has prepared in ArcGIS 10.8 application by using the 3D analyst slope tool, and then analysed over 5 degrees via reclassify [31]. As a result, the calculating the usable slope areas on the map, it was determined that 0–1.0 degree – 19.5 thsd km^2 (22.5 %), 1.1–3.0 degree – 26.1 thsd km^2 (30.1 %) and 3.1–5.0 degree – 6.7 thsd km^2 (7.8 %) (fig. 2).

In the study, closeness to settlement localities, main ways, and energy lines are appropriated as an essential factor concerning economic profit and avoiding electricity losses. Here, depending on the site of the power plant, and the amount of electricity generation, a buffer distance of 2000 m from the settlement, 300 m from the highways, and 1000 m from the power line is identified. Such a site proximity assessment provides a very effective profitability in choosing the most suitable location for the installation of a grid-connected PV solar power plant. Because the project planned for the installation of the power plant in the preferred area should be a successful offer regarding internal rate of return, discounted payback period, and employment insurance.

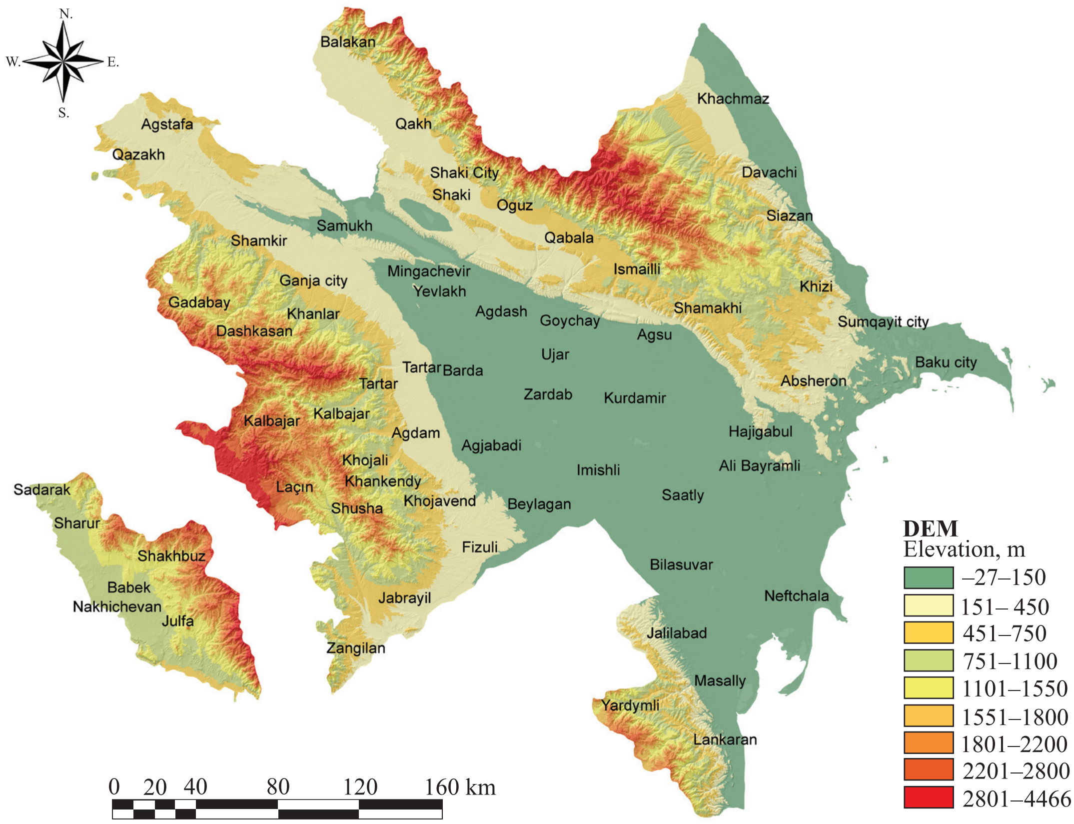

Fig. 1. Digital elevation model of Azerbaijan.
Source: [32], modified

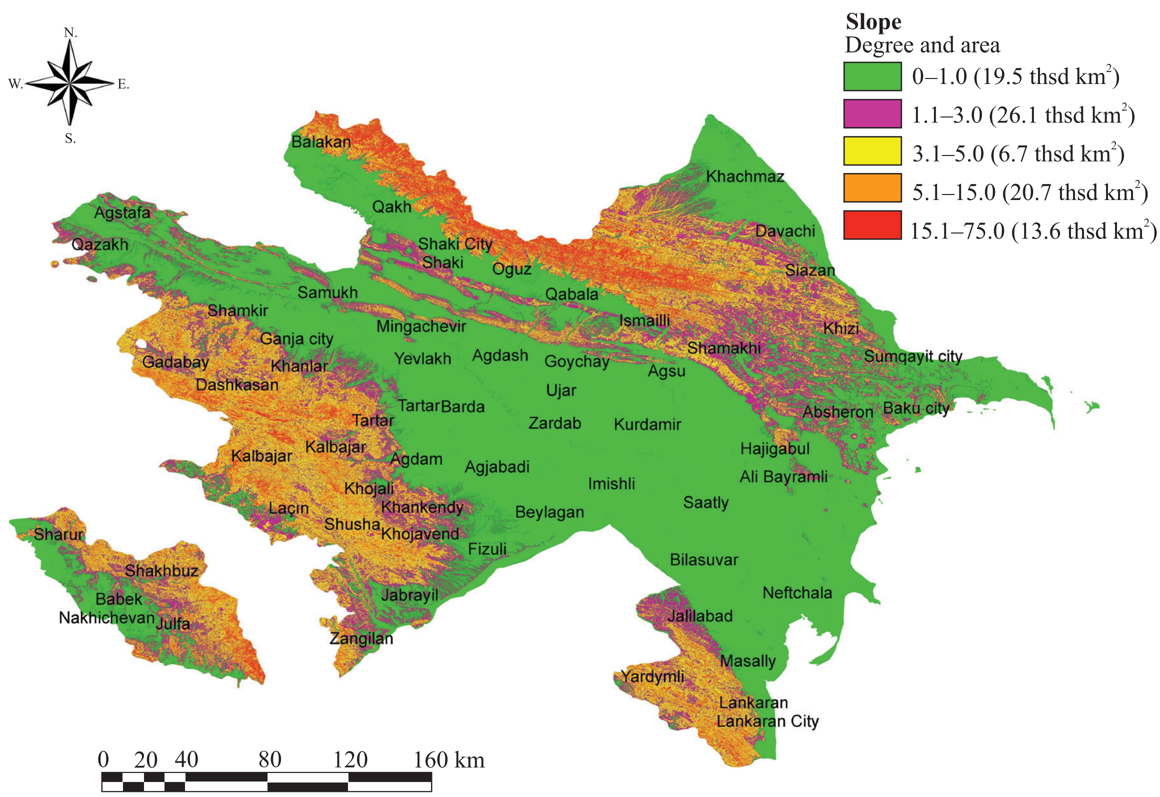

Fig. 2. Slope map of Azerbaijan.
Source: [32], modified

The protected areas, agricultural lands, national parks, industrial cities and historical places in the country are excluded from the solar power plant installation areas as restriction areas. In Azerbaijan, there are 10 national parks, 10 state nature reserves, and 24 habitat species management areas in a total territory of 8925.4 km^2 (10.3 % of the country's area) for protecting natural areas [33]. In addition, residential areas, industrial areas, woodlands, and fertile soils are considered limiting factors in site usefulness assessments [34] (see fig. 3). The buffer distances performed by data collected for the thematic layers of protected zones in this research are classified as shown in table 1. The restriction layers shown in fig. 3 were integrated into a single layer, including the required buffers.

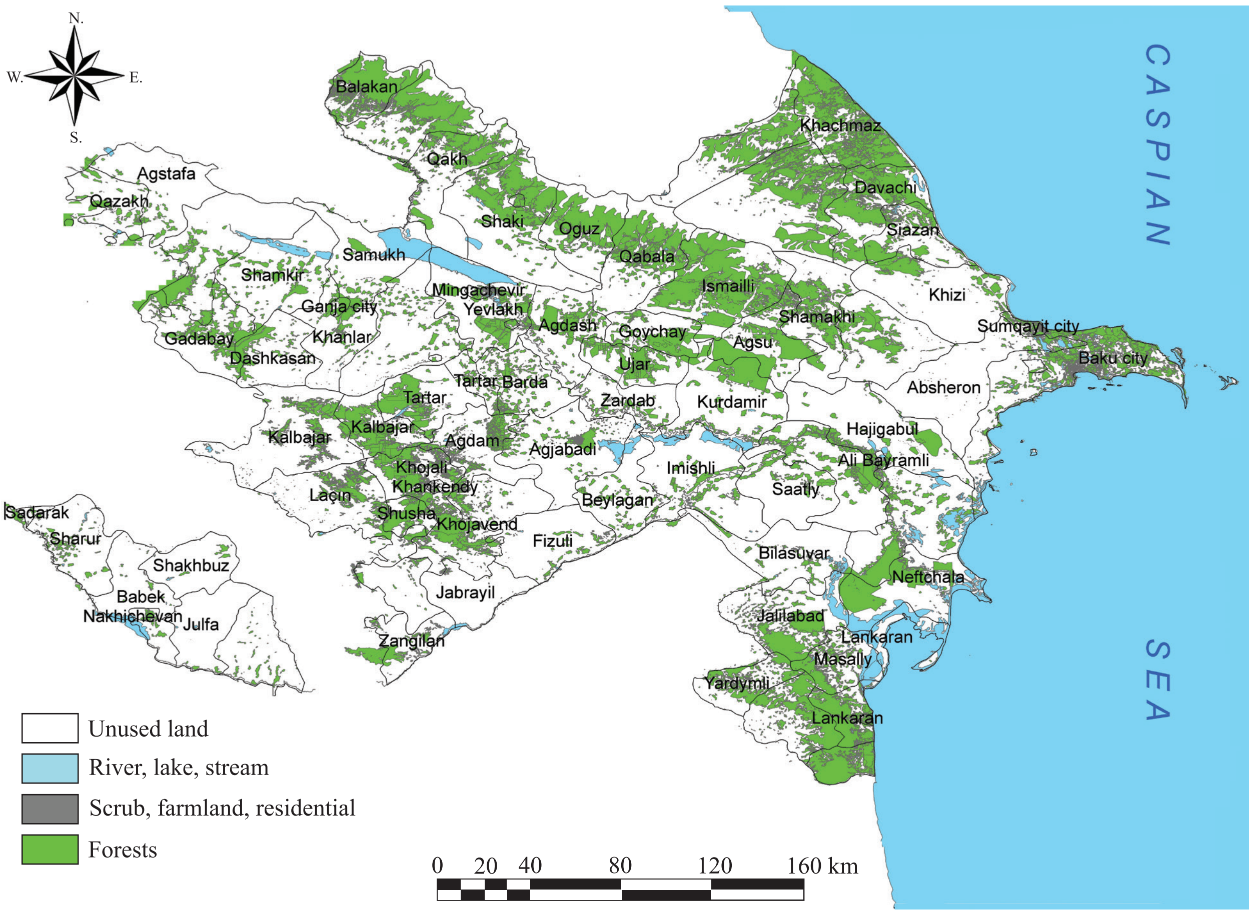

Fig. 3. Land use in Azerbaijan.
Source: [35]

The AHP method used in the study is one of the most comprehensive based on MCDM technique to identify appropriate alternatives by presenting a decision coefficient for the solution of various factors. It allows the generation of a combination of qualitative and quantitative inputs that provide an optimal approach to solution with complex criteria options in diversifying energy sources and determining the appropriate location. The AHP model has developed as an accessible MCDM technique to simplify solution result oriented investigations of such as compound decision issues [14; 20]. The AHP hierarchy sets the primary aim, whereas, the middle and lower levels show selection principles and alternatives, separately. If the DM sees a discrepancy in the results, it provides a solution to explain this discrepancy with the AHP model [17]. The DMs analyse each standard criterion in pairwise correlations against their database. As a result, it divides the criteria into smaller sub-levels through this method and is weighted corresponding to site selection principles.

AHP method in choosing a suitable site. In the study, four criteria for determining the most suitable sites: slope (see fig. 2), solar irradiation (fig. 5), land use, distance to roads, power lines, and settlement areas (see fig. 3 and 6) evaluated and decision matrix are formed by pairwise comparison of these criteria. The weight values of each criterion are defined through the suitability index equation calculations with the AHP method. A consistency ratio (CR) is then involved to eliminate contradictory decisions throughout the pairwise comparison studies. To realise the AHP method, the values of the *n* number of criteria are determined, and a set of formulas are applied in the following order [36]. To determine CR in six steps with the AHP method: 1) problem definition; 2) comparison matrix creation; 3) normalisation; 4) getting the priority vector; 5) CR; 6) selection or ranking process – is performed (fig. 4). The order of priority in the selection of suitable areas are following: 1) solar irradiation (A); 2) land use (B); 3) distance to roads and power lines (C); 4) slope (D).

First, the basic criteria are compared among themselves. In here the equations developed by Saaty [36] is used for comparisons. The preference score for criterion *j* of the *i* criterion is determined using the A_{ij} nine-integer value scales presented to create a pairwise comparison matrix with various criteria $m = n \times n$ (table 5). A_{ij} denominates the entry in the *i* row and the *j* column of matrix *m* in table 2.

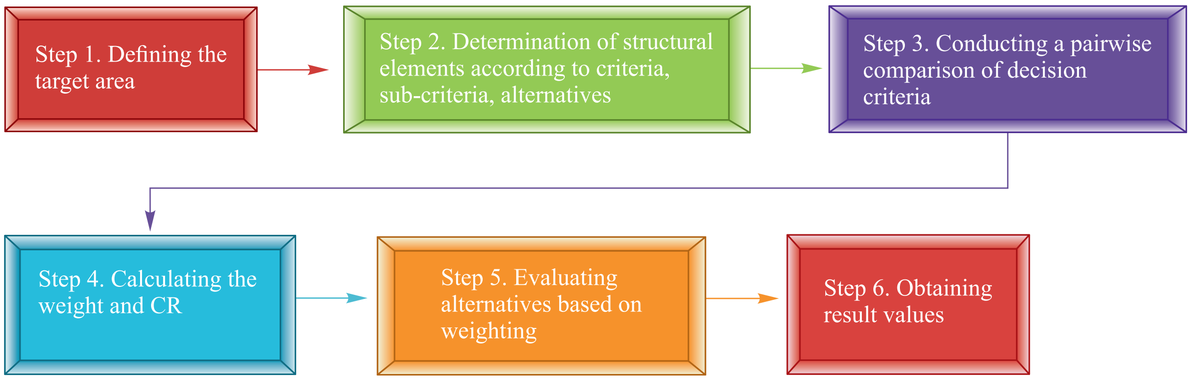

Fig. 4. Flowchart of AHP

Table 2

Comparison values performed in AHP and their interpretations

Numerical values (A_{ij})	Numbers (A_{ji})	Importance level	Definition
1	1	Equally important	Criterion *i* and *j* are of equal importance
3	1/3	Slightly important	Criterion *i* is slightly more important than *j*
5	1/5	Important	Criterion *i* is moderately more important than *j*
7	1/7	Very important	Criterion *i* is strongly more important than *j*
9	1/9	Highly important	Criterion *i* is extremely more important than *j*
2, 4, 6, 8	1/2, 1/4, 1/6	Intermediate values	

The entries of preference score A_{ij} and A_{ji} must supply the following constraint in equation (1): the comparison matrix is a $n \times n$ square matrix. The matrix components on the diagonal of this matrix take the value 1.

$$A = \begin{bmatrix} 1 & A_1 & A_2 & A_3 & \dots & A_n \\ A_1 & 1 & a_{12} & a_{13} & \dots & a_{1n} \\ A_2 & a_{21} & 1 & a_{23} & \dots & a_{2n} \\ A_3 & a_{31} & a_{31} & 1 & \dots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_n & a_{n1} & a_{n2} & a_{n3} & \dots & 1 \end{bmatrix}, \qquad (1)$$

where $a_{ij} = \frac{1}{A_{ji}}$, $i, j = 1, 2, 3, \dots, n$. Total $\frac{n(n-1)}{2}$ comparisons are made. Here, for $n = 4$, $\frac{4(4-1)}{2} = 6$.

Then, the sum of each column requirement equals 1 to create a normalised pairwise comparison matrix $\bar{m}$. This can be obtained using an equation (2):

$$\bar{A}_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}}. \qquad (2)$$

to calculate $\bar{A}_{ij}$ for each entry of matrix $\bar{m}$ in table 3.

Table 3

Comparison matrix of the accepted decision criteria

Criteria	A	B	C	D
A	1	7	5	1/4
B	1/7	1	1/2	1/7
C	1/5	2	1	1/9
D	4	7	9	1
Total	*5.34*	*17*	*15.5*	*1.50*

In the third step, the average values between rows are obtained to determine the relevant weights using a set of formulas (3):

$$W_i = \sum_{i=1}^{n} A_{ij} n^{-1}. \tag{3}$$

In here, the relative weight for each criterion is in the range 0–1. Moreover, the result of calculating the every criterion weight values, it appears that the solar irradiation factor has a greater effect on the solar PV power system. The priority vector is obtained as follows (table 4).

Table 4

Normalisation matrix $(A_{ij} = \frac{\text{Rows}}{\text{Sum of rows}})$

Criteria	A	B	C	D	Normalised priority vector (W_j)	Final weights, %
A	0.187	0.412	0.323	0.166	$\sum \frac{A_{ij}}{4} = 0.272$	28
B	0.027	0.059	0.032	0.095	$\sum \frac{A_{ij}}{4} = 0.053$	5
C	0.037	0.118	0.065	0.074	$\sum \frac{A_{ij}}{4} = 0.073$	8
D	0.749	0.412	0.581	0.665	$\sum \frac{A_{ij}}{4} = 0.584$	59

In the fourth step, to obtain the PV power plants suitability map (SM) is applied for each criterion of the layers formed within the scope of the study area in equation (4):

$$\text{SM} = \sum_{i=1}^{n} x_i \cdot w_i \cdot r, \text{ here } r \in \{0, 1\}. \tag{4}$$

If the constraint (r) comes out, $r = 0$ and this reflected on the SM value of an inadequate location. Otherwise, the SM can be obtained by finding the sum of each criterion value (x_i) multiplied by the criterion weight (w_i) (table 5).

Table 5

Weight and priority vector according to criteria

Weight	Priority	Criteria
0.272	2	A
0.053	4	B
0.073	3	C
0.601	1	D

In the fifth step, the related formula is used to calculate the CR of the obtained values in the equation (5):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \text{ here } \mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} \text{ and } Aw = \lambda_{\max} w; \quad (5)$$

$$\mathrm{CI} = \frac{4.234-4}{4-1} = 0.078, \ \mathrm{CR} = \frac{0.078}{0.90} = 0.086\ \%.$$

The CR is obtained by dividing the consistency index (CI) into the random index (RI). Here RI is the random CI that changes according to the number of criteria. Since the number of criteria in the study is four, the RI equal to this value corresponds to 0.90. To determine the CI value of the basic criteria, the maximum eigenvalue of the comparison matrix (λ_{max}) is found (table 6).

Table 6

Determining the mean value of λ_{max}

Aw	$\frac{Aw}{w}$	Mean λ_{max}
1.162	$\frac{1.162}{0.272} = 4.271$	4.234
0.215	$\frac{0.215}{0.053} = 4.035$	
0.301	$\frac{0.301}{0.073} = 4.102$	
2.722	$\frac{2.722}{0.601} = 4.525$	

Since the CR ≤ 0.10 – consistency degree is considered satisfactory, the 0.086 consistency ratio determined in the paired comparison is within the acceptable range. Four economic regions with high solar irradiation values for the installation of solar power plants throughout the country, through the AHP method: Nakhchivan, Aran, Absheron, and Ganja-Kazakh were evaluated as alternatives to each other. In choosing the suitable sites for solar power plants, the main criteria were determined from high to low scale according to their importance levels are weighted according to the GHI (A), land use (B), distance to main roads and power line (C), and slope (D) (table 7). Afterwards, the Nakhchivan region was determined as the most suitable site with the pairwise comparison matrix calculation of sub-criteria data such as irradiation (1400–1699 kW · h/m^2 – annual), land use (fertile soils, barrens), Euclidean distance (1000–5000 m), and slope (1–5°) (table 8).

Table 7

Pairwise comparative matrix calculation values of the main criteria

Criteria	Weighted values	Graphic	Alternatives	Total	Normal	Ideal	Ranking
A	0.389278 (39 %)		Nakhchivan AR	0.0812	0.3249	1.0000	1
B	0.31875 (32 %)		Aran	0.0764	0.3055	0.9404	2
C	0.27086 (27 %)		Absheron	0.0545	0.2179	0.6707	3
D	0.02128 (0.2 %)		Ganja-Kazakh	0.0379	0.1516	0.4667	4

Table 8

Weighted values of sub-criteria in choosing the suitable site

Final weight	Sub-criteria	Weighted values (>1)	Value, %
Distance to roads and power lines	1000 m diam	0.75003	75
	5000 m diam	0.24997	25

Ending table 8

Final weight	Sub-criteria	Weighted values (>1)	Value, %
Solar irradiation (annual)	1400–1500 kW · h/m^2	0.104 73	10
	1500–1600 kW · h/m^2	0.258 28	26
	1600–1699 kW · h/m^2	0.636 98	64
Land use	Barrens	0.875 00	87.5
	Fertile soils	0.125 00	12.5
Slope	0–1°	0.181 18	18
	1–3°	0.545 46	54
	3–5°	0.282 73	28

Results and discussion

The study area covers almost the whole of Azerbaijan with an area of 86.6 thsd km^2 in the South Caucasus. The country is in the arid subtropical climate zone formed under the influence of the Great Caucasus Mountains in the north, and the Caspian Sea in the east. Since the GHI values and air temperature are high, about 30 % of the country is dominated by semi-desert climate (grey soils). Fossil fuels have an important place in the country's energy policy and electrical energy supply (92.7 %). However, as a member of many of the global climate change connotations, such as the «Paris Agreement» on preventing carbon dioxide measures, the country has a future-oriented renewable energy portfolio. These include the installation of solar PV plants in the Absheron region and the establishment of smart villages in the Karabakh region. Thus, the country aims to provide 30 % of the country's electrical energy supply from wind and solar energy by 2030. As the first such scientific approach for this field of study, it is aimed to identify energy potential locations to achieve energy goals.

The GHI value in the republic was calculated as a daily average of 3.4 kW · h/m^2 or an annual average of 1240 kW · h/m^2 (minimum 705, maximum 1776) as shown in fig. 5. Across the country, areas with GHI values above 1501 kW · h/m^2 cover 21.8 thsd km^2 or 18.9 % of the total area (6th and 7th radiation scale). However, the area of 40.3 thsd km^2 (46.5 %) (5th radiation scale), which covers the Aran region with average GHI values (1450 kW · h/m^2), is potentially among the most suitable regions for solar power installations [10]. It has been determined that the average annual sunshine duration on the horizontal surfaces of 10 economic regions in Azerbaijan is 2400 h [11]. Nakhchivan AR among them is the region with higher annual sunshine duration (between 2400 and 2800 h) and GHI values (1500–1776 kW · h/m^2) throughout the country [10]. In Nakhchivan AR, the annual total cloud cover rate, which has a negative effect on solar energy production with a score on a scale of 4.0–5.5, the number of days when the maximum temperature of the air is above 35 °C is 30–40 days, annual snowy days are 20–60, the duration of the annual foggy days ranges from 10 to 50 days [29].

Sensitivity analysis. In the study, the most suitable sites are determined by analysing potential areas for PV power plants with the AHP method. These areas mainly include large-scale areas where solar energy can be applied, excluding agriculture, industry and protected areas. As can be seen from the weighted concluding map based on the AHP-GIS method, 1.17 % (1.02 bln m^2) of the study area was found to be suitable for the deployment of solar power plants. Aran region, which is the most suitable area for solar energy installation throughout the country, especially in Absheron and Nakhchivan, corresponds to a medium suitability level due to its relatively low solar radiation (1450 kW · h/m^2 per year). Other regions of the country (Sheki-Zagatala, Guba-Khachmaz, Lankaran and Kelbajar-Lachin) are included in low suitability zonas due to low-intensity solar radiation, annual cloudiness rate, insufficient relief, lack of infrastructure, and high-costs installation.

The basic criteria to determine the best sites for the deployment of solar power plants were performed below in sequence:

- first, the criteria were systematised in three groups, namely meteorological (solar irradiation and air temperature), economical (distance to a settlement area, distance to roads and distance to transformers), and topographic (slope, land aspect, relief). Here, the major purpose is to select the most efficient energy production area for PV power plants, and the input data in the model created has been divided according to 10 degrees from the highest to the lowest;
- in the second stage, the suitability level of the locations selected using the weighted overlay tool was calculated according to the determined criteria;
- in the end, in order of importance, the slope, and land features in the solar energy potential areas have been weighted in the model according to certain degrees, which are suitable for the PV power plant installation.

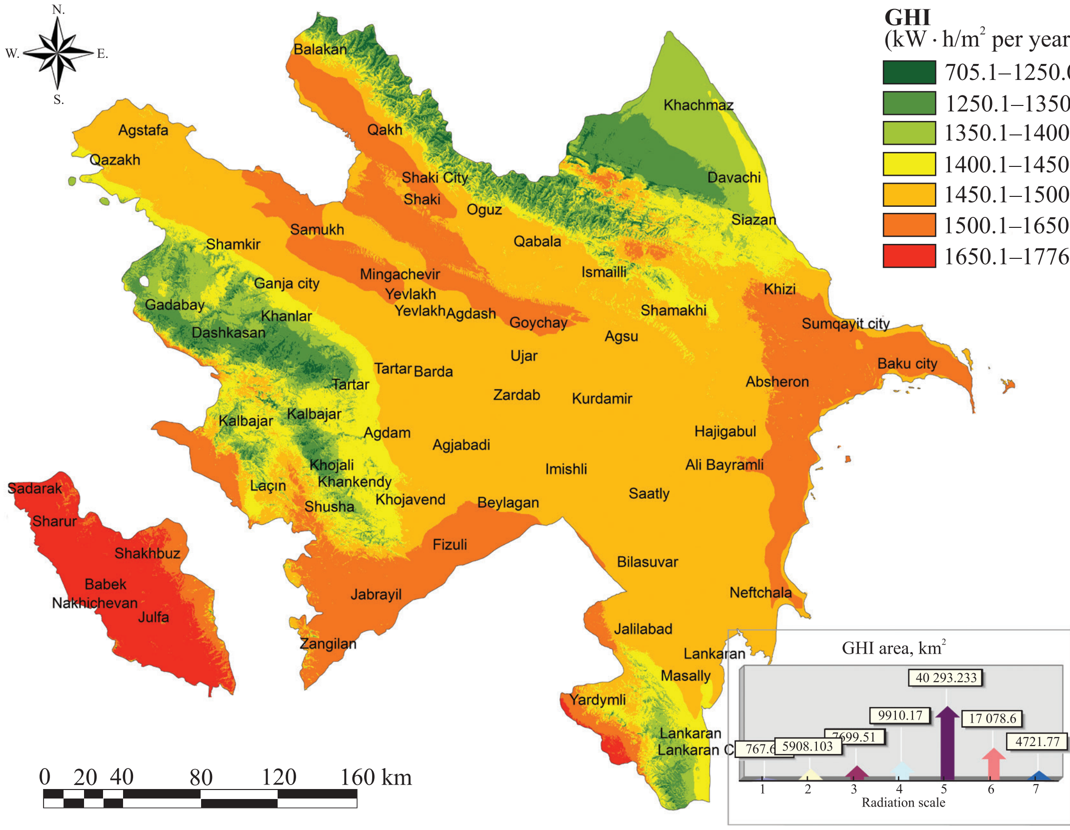

Fig. 5. Long-term average (1999–2018) of annual total GHI for Azerbaijan.
Source: [10; 11], modified

It was concluded that the Sharur, Babek and Julfa districts on the banks of the Aras River in the Nakhchivan region are the most suitable areas for the installation of solar power plants because of their higher solar insolation, intensive sunshine duration, and high sky clearness index. The mountainous zones (Greater Caucasus, Lesser Caucasus, and Talysh mountains) covering about 40 % of the country have a lower land suitability index due to major steep slopes, lack of infrastructure, etc. According to the model suitability values, Khizi, Hajigabul and Gobustan regions were determined to be moderately suitable areas for PV installation due to high electricity consumption areas, large unused areas, and moderate direct solar irradiation on the horizontal surface.

Generally, infertile lands are considered more suitable sites for installing solar power plants. As shown on the land use map of the country, the areas with average and high solar radiation values correspond to the grassy vegetation and arable land area [37]. These areas are 33.6 and 41.2 %, respectively, and cover a total of 29.1 and 35.7 thsd km^2 of the country (see fig. 6). The areas unsuitable for installing solar power plants include forests, shrubs, sparse vegetation, broad-leaved forests and settlement areas. The areas with infertile soils, bare and sparse vegetation in Nakhchivan, Absheron and Aran districts, which are the most suitable regions of the country, are in accordance with the installation principles of solar power plants. The areas in this category cover 1.2 % of the country's land with 371 km^2 in Nakhchivan, 382 km^2 in Absheron and 207 km^2 in Aran districts.

The electric capacity of all power plants in Azerbaijan amounted to 7516 MW, and the total electricity generation 26.1 bln kW · h in 2020. These, 1.9 bln kW · h (7.3 % of the total) were obtained from renewable energy sources. Renewable energy production, excluding hydropower, accounted for 1.5 % of total electricity generation or 399.1 mln kW · h. Among them, the capacity of photovoltaic solar stations is contained 37 MW (9 stations, 1 hybrid), and electricity generation 44.2 mln kW · h (efficiency, 13.7 %) [38]. Data obtained because of the research the SM, and generated from the analysis of certain criteria, not only benefits DMs, but can also help Azerbaijan achieve about 30 % of its renewable energy targets by 2030 and ensure energy security.

The final map was created with the ArcGIS model builder tool by weighting the basic criteria for selecting suitable areas (settlement, natural objects, main roads, transmission line, solar irradiation, environment and land use) (fig. 7). Optimal locations, covering 25 % of suitable areas, are located in the Absheron economic zone, where most of the country's residential and industrial areas are located. In addition, suitable sites in this region are close to major roads, power lines and settlements, and it allows to avoid additional costs for infrastructure.

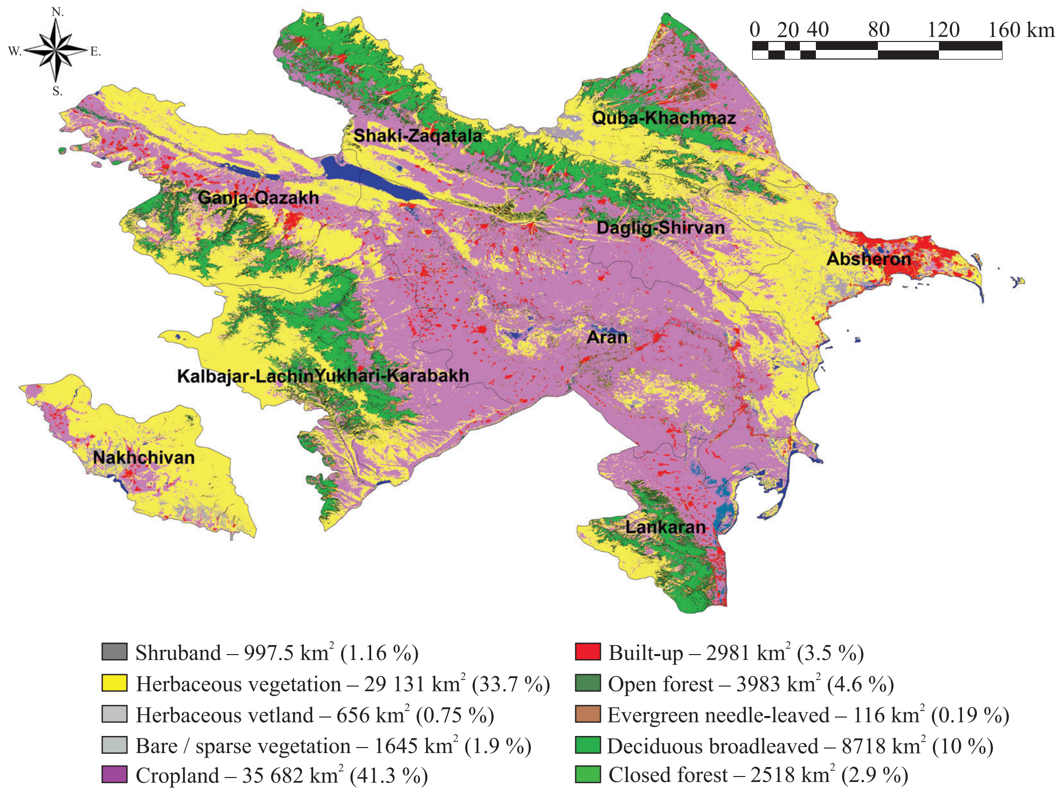

Fig. 6. The land covers composition.
Source: [37], modified

In order to calculate the site suitability values, the sensitivity analysis of the indicators that determine the grid layers were evaluated according to the weight values of the defined criteria. The main purpose here is to avoid additional costs in the installation of the power plant, 20 % weight was given to each of the economic criteria such as slope, land orientation, proximity to settlements, power lines and proximity to main roads (table 9). As result of the calculation, it has been concluded that approximately 11 % (109.2 km^2) of the suitable areas have high ratio, 28 % (284.6 km^2) – medium ratio and 61 % (623 km^2) – low ratio site suitability (table 10). Suitable alternative regions for the installation of the plant, determined according to AHP weight values of economic, environmental and meteorological criteria, are Nakhchivan, Absheron, Ganja-Kazakh and Aran, respectively.

Table 9

The calculated weight of each criterion and sub-criterion alternatives in the AHP model

Sub-criteria	Options	AHP weight (alternatives)			
		Absheron	Aran	Ganja-Kazakh	Nakhchivan
Euclidean distance to the power line	1000 m	0.642 8	0.097 24	0.208 74	0.051 22
	5000 m	0.656 96	0.075 98	0.191 08	0.075 98
Radiation (GHI)	1400–1500 kW · h/m^2	0.129 26	0.247 61	0.073 64	0.549 49
	1501–1600 kW · h/m^2	0.121 91	0.270 55	0.063 64	0.543 9
	1601–1699 kW · h/m^2	0.132 6	0.260 64	0.073 42	0.484 3
Land use	Barrens	0.389 86	0.152 35	0.067 92	0.389 86
	Fertile soils	0.084 99	0.239 89	0.582 32	0.092 8
Environment	Protected areas, natural objects	0.075 980	0.656 96	0.075 98	0.191 08
Slope	0–1.0 degree	0.118 15	0.487 45	0.276 24	0.118 15
	1–3.0 degree	0.151 18	0.508 29	0.265 34	0.075 2
	3–5.0 degree	0.117 5	0.565 01	0.262 2	0.055 29

Fig. 7. Weighting the basic criteria for suitable sites selection with a model builder

Site suitability index. The total 40 sites have been identified for the location of solar photovoltaic plants with high, medium and low levels of suitability in the country (see table 10). It covers a total area of 109.2 km^2 or 0.13 % with 8 sites in the Nakhchivan AR, which corresponds to the highest site suitability level through the country (fig. 8). With annual GHI values above 1500 kW · h/m^2, this region has the most optimal sites for the installation of solar power plants. Thus, a calculation of the possible solar energy production potential of a total area of 109.2 km^2 was made according to the formula below (6):

$$E = A \cdot r \cdot H \cdot \mathrm{PR}, \tag{6}$$

where E – energy, kW · h; A – total photovoltaic panel area, m^2; r – solar panel yield CF, %; H – annual average irradiation value on tilted panels (shadings not included); PR – performance ratio (default value – 0.75 %), and the coefficient for losses of PV plants (0.25 %).

Using this formula ($E = 109.2 \cdot 13.7 \cdot 1500 \cdot 0.75$), the possible power capacity and maximum energy output of PV plants were determined as 15 mln MV and 16.83 bln kW · h per year, respectively.

In the second stage, the area of the locations with medium GHI values (1500 kW · h/m^2 per year and over) was determined. Thus, the number of sites in the medium suitability indexes are in 12 different locations, covering a total area of 284.6 km^2 or 0.32 % of the country territory (see fig. 8). Theoretically, it is possible to install 13 573 MW (1.0 MW PV power plants is cover 21 thsd m^2 area surface) PV power plants on a total area of 284.6 km^2, which corresponds to an annual electricity generation of 16.2 bln kW · h (annual average 1.0 MW – 1.2 mln kW · h) (see table 10).

Table 10

Site suitability indicators for the installation of PV plants across the country according to GHI values

Number	Suitable sites	Location (latitude – longitude)	Area, km^2	GHI, $kW \cdot h/m^2$ per year	Possible the power of the PV plant, MW per year	Maximum possible energy output, mln $kW \cdot h$ per year
High suitable						
1	Julfa-1	38.97–45.73	2.1	1755	101	151.6
2	Julfa-2	38.97–45.65	9.2	1753	440	661.1
3	Julfa-3	39.18–45.54	4.0	1749	193	290.0
4	Babek-1	39.29–45.32	45.5	1737	2170	3256.4
5	Julfa-4	39.02–45.57	1.3	1735	61	92.4
6	Sharur	39.48–45.13	10.6	1730	507	761.3
7	Babek-2	39.25–45.22	22.8	1728	1089	1634.7
8	Sadarak	39.69–44.93	13.7	1719	653	980.4
Medium suitable						
1	Karabakh	39.21–46.87	28.3	1574	1348	1618.7
2	Zire	40.34–50.33	1.3	1523	65	78.0
3	Horadiz	39.37–47.20	1.9	1530	92	110.5
4	Sangachal	40.22–49.42	26.8	1529	1278	1533.6
5	Cheyildagh	40.30–49.37	44.6	1527	2128	2553.9
6	Gobu	40.35–49.72	4.9	1525	234	280.8
7	Qakh	41.03–46.88	102.9	1521	4900	5880.0
8	Absheron	40.52–49.58	1.9	1510	94	113.1
9	Shamkir	41.09–46.18	59.7	1506	2844	3412.9
10	Z.Tağıyev	40.67–49.43	7.8	1505	373	447.6
11	Qobustan	40.47–49.06	2.7	1503	128	154.4
12	Chilov	40.33–50.59	1.8	1502	89	106.8
Low suitable						
1	Xoylu	40.58–46.63	57.4	1497	2738	2874.9
2	Goychay	40.41–47.56	34.5	1495	1645	1727.2
3	Hajigabul	40.09–48.99	42.0	1494	2001	2101.0
4	Aghjabadi	39.76–47.36	26.2	1493	1251	1313.5
5	Kurdamir	40.23–47.90	48.9	1491	2328	2444.4
6	Neftchala	39.29–49.22	8.1	1490	388	407.4
7	Pirallahi	40.48–50.34	0.12	1488	5	5.2
8	Tovuz	41.15–45.85	96.6	1485	4599	4828.9
9	Saatly	39.67–48.76	93.2	1483	4438	4659.9
10	Beylagan	39.96–47.78	61.1	1478	2910	3055.5
11	Tartar	40.37–46.82	60.2	1476	2865	3008.2
12	Agstafa	41.41–45.35	6.1	1473	291	305.5
13	Shamakhi	40.18–48.73	26.3	1472	1251	1313.5
14	Poylu	41.32–45.50	19.6	1466	936	982.8
15	Kura Island	38.99–49.14	14.0	1466	670	703.5
16	Agdam	39.95–47.05	8.7	1465	417	437.8
17	Shurabad	40.79–49.51	8.4	1460	400	420.0
18	Khizi	40.86–49.32	2.9	1435	139	145.9
19	Zarat	40.91–49.29	6.4	1423	308	323.4
20	Siyazan	40.99–49.21	2.3	1412	110	115.5
Total						
40	Azerbaijan districts	38.97–50.59	1016.8	1412–1755	48 577	55 293.3

Sources: [17; 38].

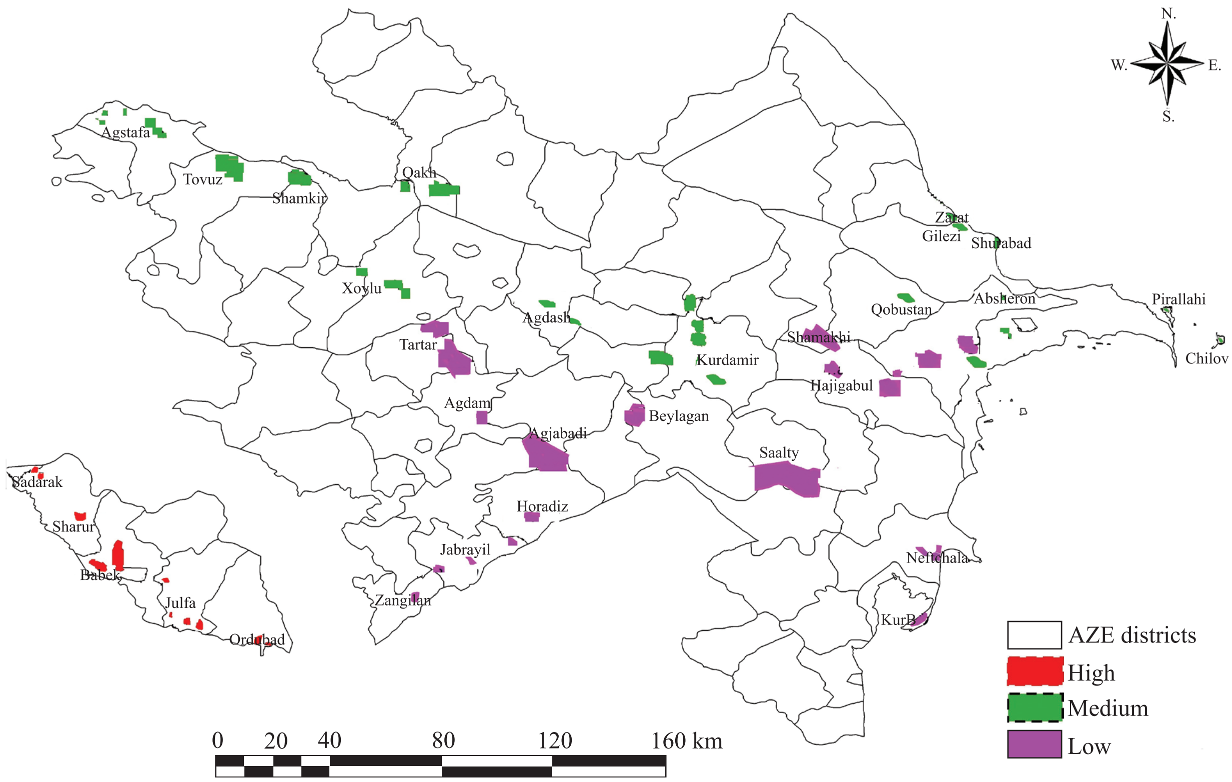

Fig. 8. Locations of optimum sites determined because of applying AHP weight criteria

Finally, suitable locations were classified into three categories according to the criteria of GHI values, clearness index, terrain relief, duration of sunny days, land use, proximity to roads and transmission lines. The total area of these optimal sites with high, medium, and low suitability indexes corresponds to 1016.8 km^2 or 1.17 % of the country (see fig. 8). These locations include areas with high suitability for the installation of PV power plants and annual GHI values above 1400 kW · h/m^2, as result of theoretically evaluating all criteria (see table 10). If the determined optimal areas are completely covered with photovoltaic panels, it is possible to achieve a total electricity generation capacity of 48.5 thsd MW and 55.2 bln kW · h (see equation (6)). This is 2.1 times more than the 26.1 bln kW · h of electricity generated in the country in 2020 [38]. The long-term use of renewable energy in the electricity supply of the country is a promising outcome for global climate change prevention and energy security. Otherwise, it is probable to occur ecological migrations as a side effect of climate change conditions soon.

Conclusion

As a result, the environmentally friendly and economic benefits of converting solar energy into electricity through photovoltaic cells, sustainable, safe and low carbon emission technologies have become more usable in recent years. In this study, according to the principles of large-scale solar power plant installation, the weights of comparison criteria such as high solar radiation, appropriate relief and high-quality infrastructure were evaluated with the AHP method and suitable areas were determined. The results obtained in the study can encourage infrastructure, energy supply et cetera developments in the selection of suitable location for solar power plants for DMs during the project design phase in this direction. For this, an appropriate result can be got by analysing geographic data based on meteorological conditions and climate as the integration of GIS with MCDM technique, evaluating the weight values of economic and technical criteria separately. The AHP method determined weights according to technical and economic factors in the site suitability model created to select the best locations for the installation of off-grid solar systems, depending on the values of solar radiation.

Due to the high initial capital investment in the solar PV power plants installation, it is necessary to determine the high potential areas to use the solar energy. For this purpose, it was present an approach that evaluates technical, environmental, geographical and economic criteria for potential areas of solar energy using the GIS based AHP model. In areas with solar power potential, basic criteria and all restrictions were evaluated and areas according to the relevance level are divided into three categories. The weighted overlay values have been an average of 45 with the analysis of the database. As a result of the calculation, 1–40 (low-appropriate), 40–70 (medium appropriate) and 70–100 (high-appropriate) values are divided according to the eligibility level on the last map. For the weight values obtained with the AHP method, each sub-criterion options are listed as in tables 8 and 9. In detail here, the solar radiation, slope, environment, main road, protected areas, settlements and other sub-criteria are weighted.

The pairwise comparisons were performed with the alternatives presented in accordance with the basic and sub-criteria over the AHP method and the relevant hierarchical structure created. In study, the calculated consistency rates were evaluated and acceptable results were made. This is a much more effective method of providing incentives for the selection and use of areas suitable for solar PV systems. For this purpose, according to the pairwise comparison evaluations made with AHP method, the consistency ratio was the most effective factor in choosing the place where solar power plants will be installation, with an average of 0.086. In addition, the average weight values from suitable areas were calculated as 1000 m from the roads and transmission line (0.750), solar radiation over 1600 kW · h/m^2 per year (0.636), infertile soils (0.870) and 1–5° slope (0.545) (see table 8).

As result of this case study, it was concluded that the most suitable areas in Azerbaijan are Absheron and Nakhchivan regions located in the east and southwest. It has been concluded that the sites suitable for solar power plant installation throughout the country have a total area of 1016.8 km^2. According to the site suitability index, 11 % (109.2 km^2) of the eligible areas are of high degree, 28 % (284.6 km^2) – medium degree and 61 % (623 km^2) – low degree. These areas mostly are located in central areas, close to urban settlements and industrial zones (see fig. 8). According to these degrees of conformity, it is possible to achieve the goals of the portfolio that provides energy security for high-intensity solar radiation, as well as using more sustainable energy sources that are compatible with the environment. In addition, government subsidies, guaranteed purchase contracts, support for securing financing conditions for the private division initiative can encourage investors inside and outside the country to invest in solar PV power development projects.

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